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Assessing the economic value of renewable distributed generation in the Northeastern American market

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ABSTRACT

Incentive programs and tax rebates are commonly offered to offset the high initial costs of small-scale renewable energy systems (RES) and foster their implementation. However, the economic costs of RES grid integration must be fully known in order to determine whether such subsidies are justified. The objective of this paper is to assess the economic value of RES, including their environmental benefits, using hourly generation information in conjunction with hourly wholesale price data. Reaching the paper's objective will provide a better estimate of the bias that could result from neglecting 1) the time pattern of the hourly wholesale price, 2) the impacts of carbon taxes on the hourly wholesale price and 3) the value of the marginal hourly GHG emissions. Selected RES include two types of grid-connected photovoltaic panels (3 kWp mono- and poly-crystalline) and three types of micro-wind turbines (1, 10 and 30 kW) modeled for different climatic conditions in the province of Quebec (Canada). The cost of electricity is based on the technical performance of these RES using a life cycle costing methodology. The economic value of RES electricity is estimated using the hourly wholesale electricity price in Northeastern American markets in 2006–2008. Results show that distributed generation (DG) has no economic benefits using the selected RES, even with a US\$100/tonne of CO_2-equivalent carbon tax. This finding remains the same when the value of the avoided GHG emissions is fully internalized, except for one scenario (micro-wind 30 kW). Our results are key to understanding the extent to which subsidies for distributed RES can be economically sustainable when the latter are integrated into regional networks driven by centralized electricity production.

Contents

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1. Introduction

Despite their high initial cost, small-scale photovoltaic and wind electricity production technologies receive significant funding [1–3]. In fact, incentive programs and tax rebates are commonly offered to offset the economic burden of the required initial capital cost. For distributed generation (DG), these incentives can significantly reduce consumer costs and therefore intensify the implementation of renewable energy systems (RES), if they are attractive enough and offered for a long enough period of time [1]. However, if the economic value of small-scale RES integration was clearly established, these financial supports could be fully justified and, consequently, more easily promoted. Indeed, such energy programs arise in a context of electricity market reforms based on increased competition and amidst talks of implementing a carbon mitigation policy such as carbon taxes [4–6].

In previous studies on the value of RES, many of their benefits were not taken into account. While certain benefits are directly valued within existing electricity markets, others are related to environmental externalities. Combining, in a detailed and integrated model, both the market and environmental value of RES is the contribution to the literature of this paper. Indeed, Borenstein [7] evaluated the economics of generating a significant portion of electricity from photovoltaic systems without including the environmental benefits. The results of this study demonstrated that, even with a 1% real interest rate and 5% annual increase in the real cost of electricity, the cost of solar PV is 80% greater than the value of the electricity it will produce. These findings were recently confirmed by Amor et al. [8], who showed that small-scale photovoltaic systems do not offer economic benefits as compared to micro-wind turbine systems in the Northeastern American market. From an another perspective, Kemmoku et al. [9] reported that the economic viability of photovoltaic panels depends on a carbon tax. Finally, Delucchi and Jacobson [5] stated that, when considering the value of air pollution and climate change damage costs (i.e. externalities), renewable options are projected to cost less than conventional fossil fuel generation.

In addition to not consistently taking these benefits into account in an integrated approach, the studies contain several methodological weaknesses. First, the economic consequences of RES were based on isolated markets, when, in fact, imports and exports of electricity play an increasingly important role in interconnected grids. Second, the hourly changes in RES production levels are fundamental, and ignoring them could lessen the relevance of the study results. In fact, knowing whether wind and solar peak production coincides with the peak electricity market price is worth exploring [3,10]. Third, integrating the value of avoided environmental externalities from other generation technologies as a result of RES production constitutes another important area of possible improvement. Indeed, in a context of carbon constraints, avoiding environmental externalities is often cited as a reason to place greater economic value on RES generation [11]. Finally, Borenstein [10] recently confirmed that more research at the interface of economics and renewable electricity market engineering would be very valuable. Such research should incorporate the value of electricity, which is very dependent on the time and location at which it is produced, and the pollution benefits from renewable generation, which are also heavily dependent on time and location.

This paper follows up on previous research assessing the economic performance of small-scale photovoltaic and wind electricity production in the Northeastern American market (Amor et al. [8]) and aims to expand the discussion on the ways in which time changes are fundamental to renewable energy systems production. The objective of this paper is to assess the economic value of RES, including their environmental benefits, using hourly generation information in conjunction with hourly wholesale price data. The results of this study will provide a better estimate of the bias that may result from neglecting 1) the time pattern of hourly wholesale prices, 2) the impacts of carbon taxes on hourly wholesale prices and 3) the value of marginal hourly GHG emissions. The Northeastern American market provides the context for the work, which is structured as follows: in Section 2, we present the economic valuation of RES generation using the hourly wholesale electricity prices in the province of Quebec neighbouring jurisdictions (Subsection 2.1) as a first analysis; modeled hourly wholesale electricity market prices using different carbon tax levels (Sub section 2.2) as a second analysis and, finally, hourly avoided GHG emissions externalities and their related economic benefits in addition to the modeled hourly wholesale price (Sub section 2.3) as a third analysis. Results corresponding to the three proposed analyses are presented in Section 3 (Sub sections 3.1, 3.2 and 3.3, respectively) and are compared to assess the bias that could result in the economic evaluation of RES generation. Finally, we draw the study conclusions.

2. Data and economic modeling approach

Before estimating the economic benefits of the studied RES (i.e. micro-wind turbine and photovoltaic panels), it is important to determine the hourly variability of the produced energy and the impacts on the final cost (US$/MWh). The selected average monthly values presented in Fig. 1 are representative of the climatic conditions in the province of Quebec (Canada). Annual wind speeds of 7, 5.6 and 3.5 (m/s) and solar radiations of 1387, 1230 and 1067 (kWh/m2/year) represent the selected above average, average and below average conditions in the province. The presented mean values of measured wind speed and horizontal solar radiations were obtained using a long-term site average dataset for Quebec (1961–1990 [12]).

Measured hourly data were not available. HOMER, the computer software evaluating grid-connected power systems and theirs applications [13], was used to generate synthesized hourly wind speeds and solar radiations from the measured average monthly values for a single year (Fig. 1). Mono- and poly-crystalline photovoltaic panels (3 kWp) with slanted roof mounting systems were selected because of their frequent installation, as were micro-wind turbines (1, 10 and 30 kW) at their respective commonly used towers heights (10, 22 and 30 m). The assumed lifetime of the moving and the fixed part of the micro-wind turbines are 20 and 40 years, respectively. For the two photovoltaic systems including their mounting systems, the assumed lifetime is 30 years. Technical specifications of the selected small-scale systems were used to compute the final energy yield. Table 1 presents the annual energy output based on the generated hourly wind speeds and solar radiation. The produced energy considers the performance of the inverter (DC/AC) including all

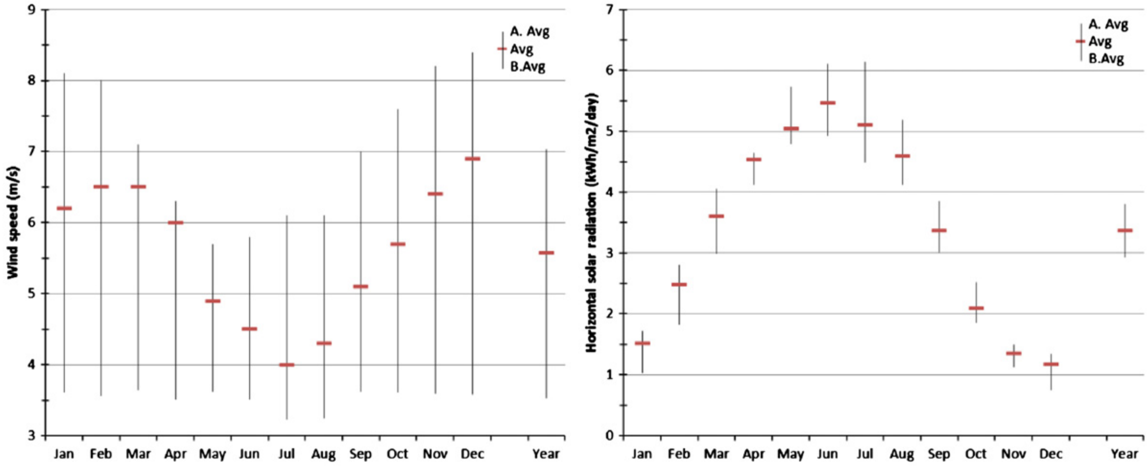

Fig. 1. Average annual and monthly wind speeds and solar radiation in Quebec (Canada), measured at 10 m (B.Avg; Avg and A.Avg refer, respectively, to below average, average and above average conditions.).

Table 1
Annual RES energy output and capacity factor for the considered climatic conditions (W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline and PVp: 3 kWp poly-crystalline).

RES	Below average		Average		Above average	
	Output (kWh)	CF[1](%)	Output (kWh)	CF(%)	Output (kWh)	CF (%)
W30	32,695	12.4	71,308	27.1	91,227	34.7
W10	10,032	11.5	22,137	25.3	29,031	33.1
W1	1004	11.5	2278	26.0	3019	34.5
PVm[2,3]	2727	10.4	3154	12.0	3559	13.5
PVp[2,3]	2727	10.4	3154	12.0	3559	13.5

[1] CF: Capacity factor is the energy output as a percentage of the theoretical maximum rated output.
[2] 3 kWp mono-crystalline (PVm) and 3 kWp poly-crystalline (PVp) produce the same amount of energy. The performance is implicitly included in the amount of panel per Wp (i.e. 21.4 m^2 and 22.8 m^2/3 kWp respectively [14].
[3] 3 kWp mono-crystalline (PVm) and 3 kWp poly-crystalline (PVp) have an efficiency equal to 15.3 and 14.4%, respectively [14].

Table 2
Life cycle cost inventory of the selected RES (W30: Micro-wind 30 kW, W10: Micro-wind 10 kW, W1: Micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp polycrystalline) [8][a].

RES	Production		Installation		Operation		End-of-life	
	US$	%	US$	%	US$	%	US$	%
W30	94,486	58	32,771	20	12,746	8	22,935	14
W10	47,900	62	13,629	18	5522	7	10,418	13
W1	7414	67	1803	16	639	6	1280	11
PVm	11,338	76	2288	15	0	0	1263	8
PVp	10,420	76	2063	15	0	0	1139	8

The life cycle cost inventory is not normalized by the final energy produced.
[a] Life cycle cost inventory of the assessed RES considers the cost of the inverter (DC/AC) including all the necessarily connections.

the necessarily connections and efficiencies (93.5% [14]) and the height of different wind towers (i.e. 10, 22 and 30 m). Previous work provides more technical details on the studied systems [8]. Total hourly energy production for a single year is presented in Table 1.

The system output is distilled down to a single measure of performance: the capacity factor (CF). CF is the ratio between the annual energy output of a given RES and its output if it were operating at full capacity all the time. Table 1 shows that in below average conditions, micro-wind turbine CF values range between 11.5 and 12.4%. These values are consistent with those reported in the literature [15]. For average and above average conditions, micro-wind turbine CF values are similar to those obtained for a commercial wind farm [15]. The same observations are noted for photovoltaic, since their CF values are also in line with typical values [16].

The annual energy output estimate is key to determining the cost (US$/MWh) for each studied RES. The cost data presented in Table 2 refers to recent work [8] and covers all life cycle stages from resource extraction and system production to the dismantling and the end-of-life of the RES. As the assessed systems are considered new technologies, a lack of knowledge still concerns their end-of-life. It was assumed that the decommissioning cost was equal to the installation cost and the landfilling cost. The landfilling cost was estimated using the landfilled materials list (i.e. not metallic parts). In coherence with previous work [8], some data were difficult to obtain since manufacturers are not always concerned by the whole RES life cycle process (e.g., do not necessarily dismantle them and did not have full control of the final cost to the consumer). Therefore, neither costs nor credits have been considered for the metals parts recycling stage[1] . We did the same for the photovoltaic modules, as no salvage value was assumed. Parameters of inflation, discount, and year of purchase were also considered in order to take into account the 'time value of money'. Once again, the operating equipment life's are 20 and 30 for the wind and solar technologies, respectively. For these calculations, a discount rate of 6% was used and the inflation was approximated at 2% based on RETScreen user manual recommendations [12]. Finally, RETScreen software was used for the results (US$/MWh) presented in Table 3.

Table 3 shows that the 30 kW micro-wind turbine posts a better life cycle cost than the 3 kWp poly-crystalline. The presented values are relatively high but stay in coherence with those found in the literature [17]. The high level is partly explained by the 6% discount rate used in the analysis. The economic values of the RES electricity once it is integrated into the grid are not considered in Table 3. The analyses in the following sections try to fill this gap by matching RES electricity production and time-dependent electricity market prices.

[1] In the province of Quebec, to the best of the author's knowledge, metallic parts could be recycled in case where the final consumers bring them to the recycling facility. However, such service is paid by the consumer taxes and no economic benefits are provided until now.

Table 3
RES Life cycle cost (US$/MWh) and geographical variations (W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp poly-crystalline).

RES	Below average	Average	Above average
W30	405	186	145
W10	690	313	239
W1	969	427	322
PVm	441	383	340
PVp	409	355	315

2.1. First analysis: RES benefits considering the hourly electricity market price

Every year, Hydro-Quebec (HQ), a government-owned utility, sells 165 TWh of hydroelectricity at a regulated cost of Can$27.90/MWh[2] to Quebec consumers [18]. In comparison to RES electricity production costs (Table 3), renewable RES is therefore not a particularly wise policy initiative from an economic perspective.

The total energy requirements exceed 165 TWh, and power must be purchased from other producers at higher and non-regulated prices. Since Quebec and its adjacent jurisdictions (New Brunswick, New England, New York and Ontario) are well interconnected, the latter actively trade electricity. Therefore, the estimate of the economic value of RES generation is formulated within the context of electricity trade. Indeed, when the province of Quebec imports, RES generation could partially replace the imported electricity, and the province could avoid import costs. On the other hand, when Quebec exports, RES generation is exported to adjacent markets, generating benefits based on variable electricity market prices. The 2006–2008 hourly electricity market prices are taken from ISO New England [19], NY ISO [20] and the Ontario IESO [21]. There is no established spot market for New Brunswick, and the New England spot price at the New Brunswick interconnection was used as a market price proxy. Once again, a discount rate of 6% is used in coherence with RES life cycle cost estimates. In this analysis, RES economic values are defined as the difference between their life cycle cost (see Table 3) and the hourly market price in jurisdictions adjacent to Quebec (as defined in their respective spot markets).

2.2. Second analysis: RES benefits considering different carbon tax levels

RES aim to help reach energy policy goals such as GHG emissions reductions. These energy programs arise out of electricity market reforms based on increased competition and amidst talks of implementing a carbon mitigation policy such as a carbon tax [4,5]. Indeed, political actions suggest that there may soon be either an explicit or implicit price on GHG emissions [6]. This section aims to explore the extent to which RES economic values change according to carbon tax levels. With a price on emitted CO_2 (e.g. US$20/Tonne CO_2), the marginal costs of a generator will increase based on the generator's CO_2 emissions (e.g., a cost increase for the coal power plant in Ontario of US$18.8/MWh=0.94 t CO_2/MWh (see Table 6) * US$20/Tonne CO_2). This cost increase will also lead to an increase in the electricity price, determined by the partial equilibrium model (explained in more details in Sub sections 2.2.1–2.2.3). This is explained by the fact that electricity price at any hour is set by the generator at the margin (i.e. generation technology and fuel available for dispatch to meet the load in the region and in real time).The partial equilibrium model, simulating the impacts of carbon taxes on hourly electricity market prices, was developed in three steps:

2.2.1. Analyzing hourly electricity demand data

The Ontario, New York and New England electricity markets are open and competitive, and their respective hourly electricity demands and hourly electricity market prices are publicly available on their respective independent electricity system operator websites [19,22,23]. For New Brunswick, hourly electricity demand is mentioned in the historical system information section and is available on the website of its corresponding system operator [24]. For the 2006–2008 period, compiled electricity demand data in combination with hourly electricity market price are used to estimate 26,300 hourly linear demand curves for every jurisdiction.

$$X^{D}{}_{j,h} = a_{j,h} - (b_{\mathrm{j,h}} P_j^D, h) \tag{1}$$

with

$$b_{j,h} = -\varepsilon (X_{j,h}^D / P_{j,h}^D) \tag{2}$$

$$a_{j,h} = X_{j,h}^D + (b_{j,h} P_{j,h}^D) \tag{3}$$

In Eqs. (1)–(3), $X_{j,h}^D$ is the demand (in MWh) and $P_{j,h}^D$ is the electricity market price (in US$/MWh). In addition to these parameters, a price elasticity ε is used to calculate the value of the parameters $b_{j,h}$ and $a_{j,h}$ with h and j representing the hour and the jurisdiction. A price elasticity value of -0.15 is used in the first step, since this elasticity value reflects the short-term (in)elasticity of electricity consumption [25]. Sensitivity analyses using different elasticity values (from -0.05 to -0.5) are also simulated to test the robustness of the study conclusion. Finally, the demand function is illustrated in Fig. 2.

2.2.2. Analyzing hourly supply and short run marginal cost curve

Table 4 presents the breakdown of the generation capacity in the province of Quebec adjacent jurisdictions. Once 2006–2008 generation capacities are determined, fuel costs (short run marginal cost, in US$/MWh) were estimated using previous work [4]. Briefly, these estimations are based on the fuel market prices (i.e., US$ per short tonne of coal, thousand cubic feet of natural gas and barrel of oil) and on the appropriate heat rate (Btu/kWh) per power plant type in each of the jurisdictions considered in the study. The significance of the fuel costs resides in the determination of plant order according to merit (also called the *to-be-operated queue*) [26]. For nuclear, hydropower and *other renewable* power plants, fuel and variable operating costs were taken from the literature [6] and considered to be the same in 2006–2008. *Other renewable* includes municipal solid waste, other biomass, geothermal, solar thermal, photovoltaic and wind energy (see note Table 4). Finally, hourly fuel costs in combination with capacity values were used to estimate 26,300 hourly linear supply curves for each of the four jurisdictions j:

$$C_{j,h}^S = a_{j,h} + (b_{j,h} X_{j,h}^S) \tag{4}$$

In Eq. (4), $C_{j,h}^S$ is the estimated marginal supply cost (in US$/MWh) and $X_{j,h}^S$ is the quantity produced (in MWh). A simple linear regression is used to calculate the value of parameters $\alpha_{j,h}$ and $\beta_{j,h}$.

[2] As underlined by the reviewer, the presented regulated cost is quite below the cost of electricity provided to final residential costumers (US $68.1/MWh—in 2008). Indeed, the regulated cost does not include the transmission and distribution costs. These costs are the same (per MWh) when we compare, from Hydro-Quebec (HQ) perspective, the government-owned utility, the two electricity production options (i.e., centralized and distributed generation). Readers can also notice that in case where US $68.1/MWh is considered, the assessed RES are still not attractive from the economic perspective (in comparison to Table 3).

Table 4
Electricity generation capacity by fuel type in MW in 2006, 2007 and 2008 [27–29].

	New England[1]			New York			New Brunswick		Ontario	
	2006	**2007**	**2008**	**2006**	**2007**	**2008**	**2006**	**2007–08**	**2006**	**2007–08**
Coal-steam turbines	613	613	613	4014	3570	2899	2150	2149	9818	9748
Petroleum	1667	1635	1635	7241	7286	7273	14	14	75	66
Steam turbine	1547	1445	1496	6870	6658	6240	–	–	–	–
Gas turbine	104	96	86	295	370	722	–	–	–	–
Internal combustion	12	29	31	53	56	88	–	–	–	–
Combined cycle	4	65	22	23	202	223	–	–	–	–
Natural gas	3009	2977	2850	16,816	16,727	16,554	769	769	1876	1599
Combined cycle	2647	2525	2372	9730	9963	9494	–	–	–	–
Gas turbine	341	440	470	899	1115	2091	–	–	–	–
Steam turbine	21	11	8	6142	5529	4934	–	–	–	–
Internal combustion	–	–	–	45	120	34	–	–	–	–
Nuclear	1864	1865	1865	5156	5156	5264	680	680	11,990	11,990
Hydroelectric	1540	1520	1552	4307	4301	4299	936	923	8349	8350
Other renewable[2]	1479	1569	1580	2017	2083	2431	–	–	414	414
Total capacity	**10,172**	**10,179**	**10,095**	**39,550**	**39,121**	**38,720**	**4549**	**4535**	**32,521**	**32,166**

Note: For US jurisdictions, it is possible to disaggregate natural gas and oil capacity as a function of prime mover. This additional step (breaking down a plant's capacity by fuel and prime mover) helps to provide detailed fuel cost data, not only as a function of the fuel type but also as a function of the prime mover (for example, natural gas combined-cycle plants are dispatched at a lower fuel cost than natural gas steam turbine plants). For ON and NB, data come from Statistics Canada, which reports thermal capacity by technology type (steam, internal combustion and combustion turbine) rather than by fuel like the EIA in the US. However, since the dominant fuel for steam power plants is coal, for internal combustion is oil and for combustion turbine is natural gas, the two groups were merged accordingly.

[1] New England refers to the states of Maine, New Hampshire and Vermont. The other New England states (Massachusetts, Rhode Island and Connecticut) are not considered because they do not share a border with Quebec and therefore do not trade electricity with the province.

[2] *Other renewable* includes municipal solid waste, other biomass, geothermal, solar thermal, photovoltaic energy and wind.

Table 5
2006–2008 electricity market price comparison without carbon tax (US$/MWh), where P and P′ refer to the market price provided by the independent system operator and the modelled price using the partial equilibrium model, respectively.

	New England		New York		New Brunswick		Ontario	
	P	P′	P	P′	P	P′	P	P′
Stdev	20.0	19.5	20.0	23.8	20.9	17.2	24.6	17.7
Min	20.8	32.2	−944.7	1.4	10.6	31.3	−27.5	−38.3
Max	218.9	168.7	191.9	211.3	213.4	127.7	611.7	207.9
Median	64.2	62.7	58.5	55.1	62.7	58.4	38.0	39.1
Average	66.0	66.7	59.6	59.7	65.3	63.0	43.8	41.6
Correlation coefficient	0.63	0.76	0.71	0.67	–	–	–	–

Table 6
Operation stage GHG emission rates (tonne CO_2eq/MWh) by fuel type and prime mover (ST, GT, IC and CC refer to steam turbine, gas turbine, internal combustion and combined cycle) [4].

		Operation stage GHG emissions (tonne CO_2eq/ MWh)									
		New York				New England				Ontario	New Brunswick
		ST	GT	IC	CC	ST	GT	IC	CC		
Coal	2006	0.99	–	–	–	1.09	–	–	–	0.94	0.91
	2007	0.99	–	–	–	1.09	–	–	–	–	–
	2008	0.98	–	–	–	1.11	–	–	–	–	–
Natural gas	2006	0.60	0.65	0.64	0.38	0.71	0.52	–	0.38	0.62	0.45
	2007	0.60	0.52	0.65	0.39	0.91	0.44	–	0.38	–	–
	2008	0.61	0.55	0.74	0.39	0.78	0.44	–	0.38	–	–
Oil	2006	0.85	1.09	1.15	0.67	0.93	1.35	0.81	0.57	1.26	0.84
	2007	0.84	1.05	0.98	0.87	0.93	1.31	0.92	0.58	–	–
	2008	0.86	1.05	1.09	0.49	1.04	1.50	0.88	0.60	–	–
Hydropower and nuclear[1]	2006	–	0		–	–	0			0	0
	2007	–	–	–	–	–	–	–	–	–	–
	2008	–	–	–	–	–	–	–	–	–	–

Note: Emissions rate estimates do not cover all life cycle stages (i.e., resources extraction including installation to infrastructure decommissioning), since carbon taxes do not yet consider these emissions.

[1] Hydropower and nuclear operation stage GHG emission rates are equal to zero. Nuclear energy is a base load technology with almost no flexibility. Its operation is unavoidable in the short term and its emissions should therefore not be assigned [30].

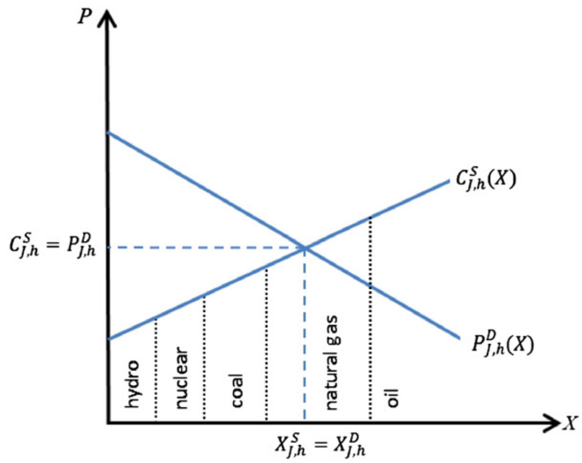

Fig. 2. Partial equilibrium illustration between the demand and supply function at given hour h and jurisdiction j.

Once again, h and j represent the hour and the jurisdiction. Finally, the supply function is also illustrated in Fig. 2.

2.2.3. Estimating the hourly electricity market price at equilibrium

Using the demand function Eq. (1) and the supply function Eq. (4), it is possible to express the demand $X^D_{j,h}$ and the electricity market price $P^D_{j,h}$ as a function of the parameters $a_{j,h}$, $b_{j,h}$, $\alpha_{j,h}$ and $\beta_{j,h}$, for every hour. Knowing that, at equilibrium, $C^S_{j,h}=P^D_{j,h}$ (see Fig. 2), Eqs. (1) and (4) give

$$X^D_{j,h}=(a_{j,h}-(b_{j,h}a_{j,h}))/[1+(b_{j,h}b_{j,h})] \quad (5)$$

$$P^D_{j,h}=\left(a_{j,h}-X^D_{j,h}\right)/b_{j,h} \quad (6)$$

In order to assess the adequacy of the proposed partial equilibrium model, the obtained hourly electricity market price $P^D_{j,h}$ in the absence of carbon taxes should be close to the compiled hourly electricity market price provided by the independent electricity system operator (ISO New England [19], NY ISO [20] and Ontario IESO [21]). Table 5, which compares both data sets for each jurisdiction, shows the adequacy of the proposed partial equilibrium model. Indeed, the assessed parameters demonstrate that estimated values using the proposed partial equilibrium model are representative of those from the independent electricity system operator. The proposed model can therefore be used to estimate the new values of hourly electricity market price $P'^D_{j,h}$ for different carbon tax levels. However, GHG emissions rates by fuel source in each adjacent market to the province of Quebec must also be known. Table 6 presents the values that were used.

For every carbon tax value, new values are obtained for parameters $\alpha'_{j,h}$ and $\beta'_{j,h}$ along with new values for the hourly electricity market price $P'^D_{j,h}$. Indeed, referring to Fig. 3, for a given carbon tax, a new supply function is estimated $C'^S_{j,h}$ (see linear regression with carbon taxes in Fig. 3), and new values are obtained for parameters $\alpha'_{j,h}$ and $\beta'_{j,h}$. At the new equilibrium point ($P'^D_{j,h}=C'^S_{j,h}$), the new value of the hourly electricity market price $P'^D_{j,h}$ is estimated using Eqs. (5) and (6) (with parameters $a_{j,h}$, $b_{j,h}$, $\alpha'_{j,h}$ and $\beta'_{j,h}$). Once $P'^D_{j,h}$ is determined, the economic benefits of RES can be estimated from the difference between their life cycle cost (see Table 3) and the new hourly electricity market price $P'^D_{j,h}$. The constructed dispatch curves are essentially short run marginal cost curves, reflecting the fuel costs, variable operating costs and carbon dioxide generation emissions costs in each jurisdiction adjacent to Quebec. It is important to note that in this partial equilibrium analysis, the impacts of carbon taxes on the fuel market prices (i.e., US$ per short tonne of coal, thousand cubic feet of natural gas and barrel of oil) are not included. Important changes to these prices may alter the merit-based plant ranking.

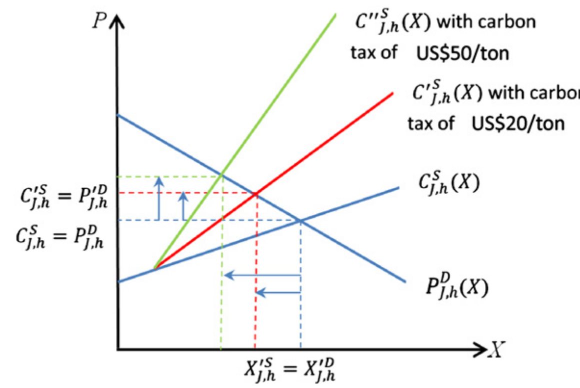

Fig. 3. Partial equilibrium illustration and carbon tax analysis at a given hour h and jurisdiction j.

2.3. Third analysis: adding the value of avoided GHG emissions

The electricity generated by the RES in this study would have to offset the emissions of traditional power generation (i.e., centralized). A previous analysis presented in Section 2.2 does not consider the avoided GHG emissions and its related economic benefits. The suggested analysis aims to bridge the gap by going one step further and internalizing the externalities that correspond to the avoided GHG emissions. If one of the selected RES is not producing electricity, no centralized electricity generation offsets could occur in the given hour. During RES generation, the province of Quebec could be importing or exporting electricity from or to the adjacent jurisdictions. It is assumed that when Quebec imports (due to increased electricity demand), the marginal technology in the adjacent jurisdictions that will be in operation to meet Quebec's demand will decrease its production in the amount that the RES are able to cover. In the same way, when Quebec exports electricity, the marginal technology in the adjacent jurisdictions will decrease its production in an amount equivalent to RES production, since less is required from the marginal technology. The marginal consequence of RES generation (i.e. the decrease in electricity production of the marginal technology located in the markets adjacent to Quebec) is assumed to be proportionate to the magnitude of RES generation due to unavailable data on transportation losses. The method presented in the following sections introduces the modeling process advanced to internalize the externalities that correspond to the avoided GHG emissions.

2.3.1. Determination of the hourly marginal electricity production technologies

To single out a marginal electricity production technology, the first step refers back to previous work (see Section 2.3 and Table 4 of previous work [4]) and briefly consists of comparing the hourly electricity market prices (see Section 2.2.1) to the estimated fuel costs (see Section 2.2.2) for each studied jurisdiction. The marginal electricity production technology is defined as the last power plant in the merit-order of all power plants needed to meet the electricity demand and whose output varies with small changes in local market conditions (i.e., an increased demand due to Quebec imports or a lower requirement for local supply due to Quebec exports). The determination of the hourly marginal electricity production technology was repeated for every carbon tax level (from 0 to 100 US$/tonne CO_2eq).

2.3.2. *Matching RES electricity production and the hourly marginal electricity production technology*

Once hourly marginal electricity production technologies are identified for each of the studied jurisdictions, matching these data with the hourly electricity production of the RES is straightforward. Indeed, for every hourly RES production, it is important to know which power plant is the marginal one in each jurisdiction. Once again, the marginal electricity production technology is assumed to curb its production and therefore avoid emissions during RES electricity production. Finally, the step is repeated for every carbon tax level (from 0 to 100 US$/tonne CO_2eq).

Table 7
RES loss (production cost minus revenue) (US$/MWh) and geographical variations (W30: micro-wind 30 kW, W10: micro-wind 10 kW, W1: micro-wind 1 kW, PVm: 3 kWp mono-crystalline, PVp: 3 kWp poly-crystalline).

Market	Climatic conditions	W30	W10	W1	PVm	PVp
New Brunswick	B Average	316.96	586.76	850.15	347.89	317.51
	Average	113.12	233.24	341.28	296.70	270.29
	A Average	74.95	163.17	242.31	255.44	232.01
New England	B Average	316.96	586.76	850.15	347.89	317.51
	Average	109.79	229.80	337.76	293.47	267.05
	A Average	72.67	160.73	239.81	252.30	228.87
New York	B Average	323.94	593.68	857.09	354.13	323.75
	Average	117.39	237.48	345.49	299.92	273.51
	A Average	79.34	167.48	246.59	258.54	235.11
Ontario	B Average	337.40	607.21	870.59	364.50	334.11
	Average	131.15	251.25	359.25	310.76	284.34
	A Average	93.36	181.47	260.57	268.99	245.57

2.3.3. *Estimation of the avoided GHG emissions and internalization*

The estimation must be carried out by using the emission rates of each of the hourly marginal electricity production technologies identified in each market adjacent to Quebec (Table 6). In a given hour, GHG abatements by the assessed RES (e.g., 30 kW micro-wind turbine) are equal to the GHG emissions (not emitted) of the affected centralized marginal electricity production technology (decreased electricity production). The hourly avoided GHG emissions is multiplied by the value of the carbon tax (of a given level), and the result is added to the new value of the hourly electricity market price $P'^{D}_{j,h}$ determined in Section 2.2. This is repeated for each hour in the 2006–2008 period and for every carbon tax level (from 0 to 100 US$/tonne CO_2eq).

3. Results and discussion

3.1. *First analysis: RES benefits considering the hourly electricity market price*

In comparison to previous work [8], RES and micro-wind 30 kW in particular were identified to be economically feasible only at above average climatic conditions. Refining the estimate by integrating the time variability of RES electricity production and matching it with the hourly electricity market price reveals lack of benefits in today's electricity market conditions. In fact, Table 7 results show that the RES electricity cost is much greater than its market value. In this analysis, the RES economic value is defined as the difference between the life cycle cost (see Table 3)

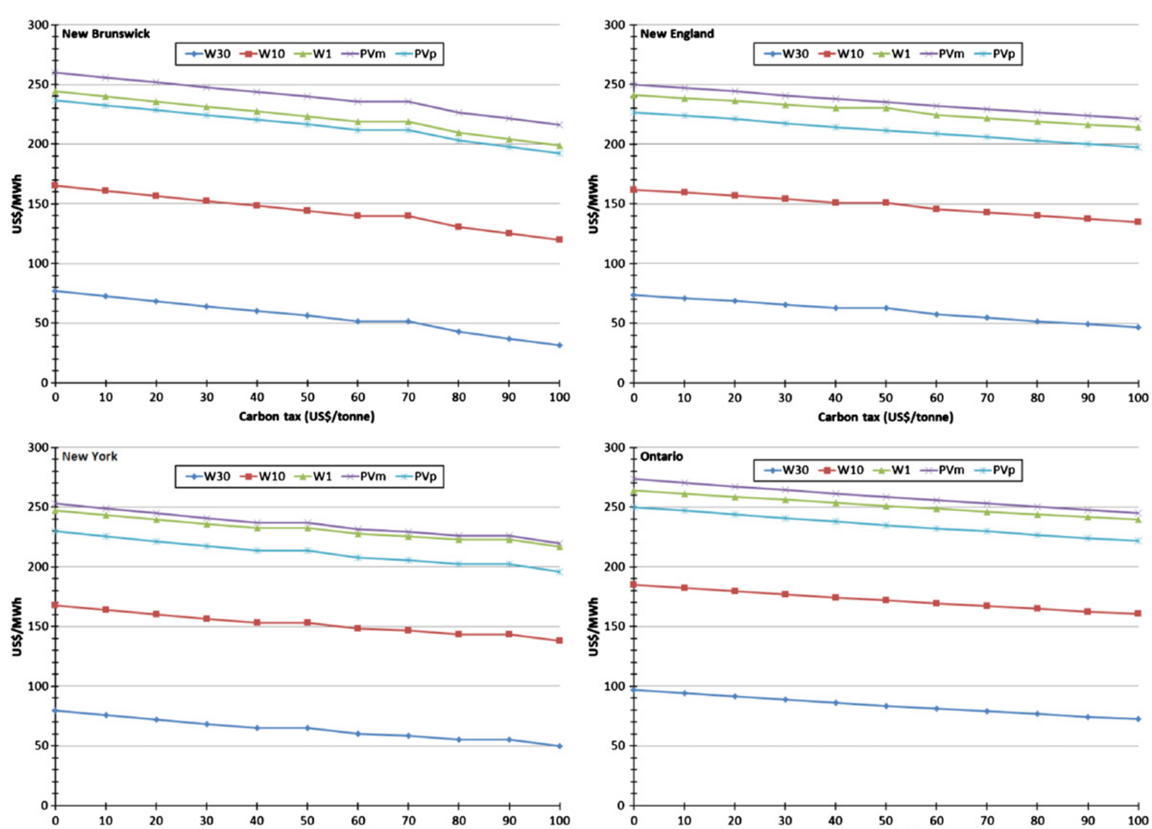

Fig. 4. Net cost of RES production in markets adjacent to Quebec and for carbon taxes ranges using an elasticity value of −0.15 (Above average climatic conditions in Quebec; W30, W10, W1, PVm and PVp refer to micro-wind 30 kW, micro-wind 10 kW, micro-wind 1 kW, 3 kWp mono-crystalline, 3 kWp poly-crystalline.).

and the hourly market price in jurisdictions adjacent to Quebec (defined in their respective spot markets, see Section 2.1). Therefore, a positive value indicates the significance of the life cycle costs of RES. This is mainly explained by the high RES acquisition cost, commonly confirmed with recent publication assessing the technico-economic feasibility of small scale renewable technologies [5,7,31]. Keeping in mind that renewable distributed generation programs arise out of electricity market reforms with talks of implementing a carbon mitigation policy such as carbon taxes [4,5], considering the impacts of carbon taxes on hourly electricity market prices is therefore justified when assessing the extent to which RES could be economically feasible.

3.2. Second analysis: RES benefits considering different carbon tax levels

Referring to the partial equilibrium model that was developed (Section 2.2), different levels of carbon taxes (from 0 to 100 US$/tonne CO_2eq) are simulated. For every level, new values of the parameters $\alpha'_{j,h}$ and $\beta'_{j,h}$ are obtained and, consequently, new $P'^{D}_{j,h}$ hourly electricity market price values are determined using Eqs. (5) and (6) (see Fig. 3). Using the estimated new hourly electricity market price $P'^{D}_{j,h}$, the economic benefits of RES are estimated in keeping with the first analysis (Section 2.1) and using the difference between their life cycle costs (see Table 3) and the new hourly electricity market price $P'^{D}_{j,h}$. Therefore, a positive value indicates a lack of economic benefits and significant life cycle costs for RES. A price elasticity value of −0.15 is used in the first step, and this elasticity value reflects the short-term (in) elasticity of electricity consumption [25]. In the second step, a sensitivity analysis using different elasticity values (from −0.05 to −0.5) is used to test the robustness of the study conclusion.

Without a carbon tax (US$0/tonne), Fig. 4 results from the proposed partial equilibrium model are coherent with Table 7 results from real data from the various system operators in jurisdictions adjacent to Quebec. Indeed, a maximum difference of 3% between the results is noted. For above average climatic condition in Quebec, Fig. 4 shows that even if the net cost of RES production decreases, as long as the carbon tax increases, the economic benefits are still lacking for the different simulated market conditions (i.e. carbon tax levels). This means that the RES acquisition cost is so high that it cannot be addressed by increasing the hourly electricity market price with carbon taxes. These observations remain the same for different elasticity values (from −0.05 to −0.5) and different climatic conditions in Quebec (average and below average conditions).

3.3. Third analysis: adding the value of avoided GHG emissions

The estimated emissions reductions from displaced traditional electricity generation depend on the timing of RES generation. Fig. 4 results do not consider the avoided GHG burdens and related additional economic benefits. During RES generation, the province of Quebec could be importing or exporting electricity from or to adjacent jurisdictions. It is therefore assumed that when Quebec imports electricity due to increased electricity demand, the marginal technologies in the adjacent jurisdictions that respond to Quebec's imports will decrease their production proportionally according to the amount of electricity that RES are able to provide. It is also assumed that when Quebec exports electricity, the marginal technologies in the adjacent jurisdictions

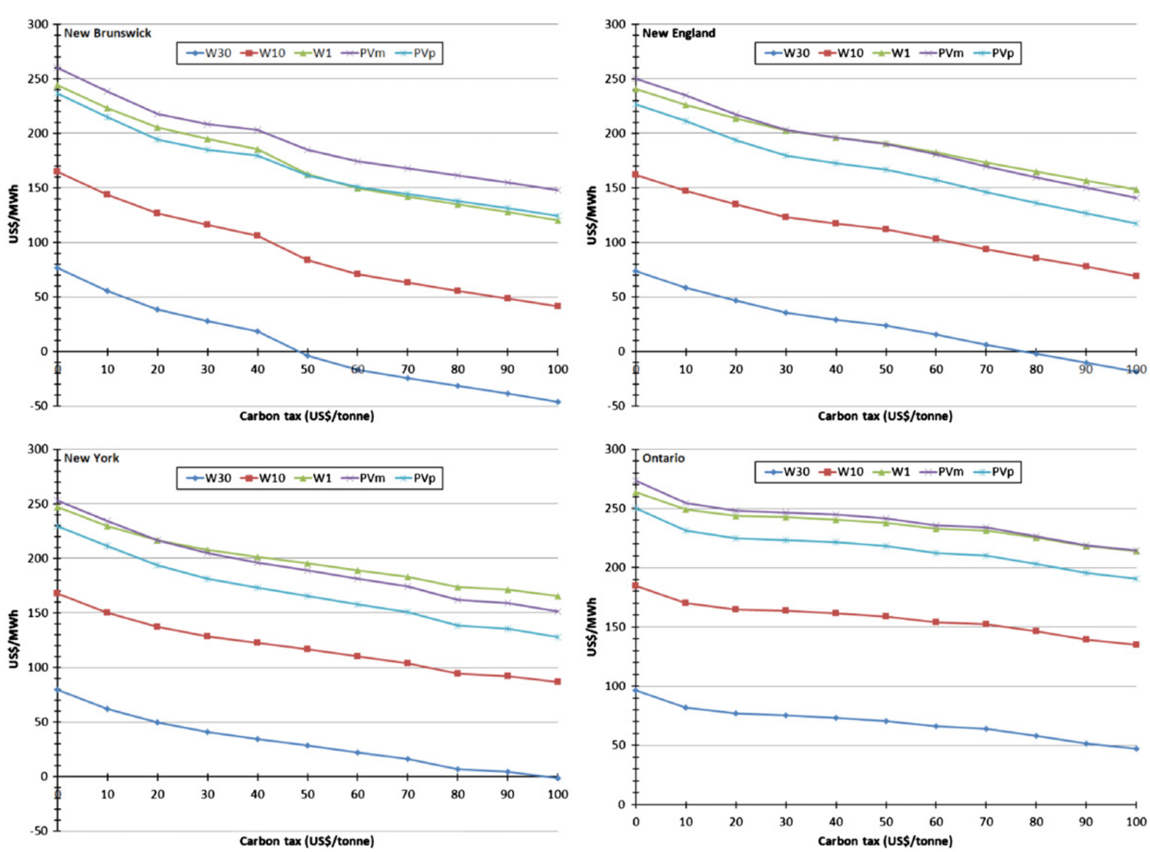

Fig. 5. Net cost considering the economic benefits of avoided emissions as a consequence of RES production in markets adjacent to Quebec and for carbon tax ranges with an elasticity value of −0.15 (Above average Quebec climatic conditions; W30, W10, W1, PVm and PVp refer to micro-wind 30 kW, micro-wind 10 kW, micro-wind 1 kW, 3 kWp mono-crystalline, 3 kWp poly-crystalline).

will decrease their production, since less is required of these technologies proportionally based on RES production. Fig. 5 results aim to bridge the gap by going one step further in the analysis and internalizing the externalities that correspond to the avoided GHG emissions due to RES generation. For above average conditions, RES and micro-wind 30 kW in particular is determined to be economically feasible in the New Brunswick market with a carbon tax equal to US$50/tonne. This is also the case for the New England jurisdictions with a carbon tax equal to US$80/tonne and is the case for the New York jurisdiction with a carbon tax over US$100/tonne. No economic benefits are noted for the Ontario jurisdiction since hydropower is the most frequently used marginal technology and therefore does not generate GHG burdens. Finally, regardless of the scenarios, for the other assessed technologies, the RES acquisition cost is once again high enough that, even for above average conditions, it cannot be covered by the increase in electricity market prices with carbon taxes and the internalization of the avoided burdens. This third analysis clearly highlights the extent to which a high acquisition cost could hinder the implementation of distributed RES generation within an energy policy. In fact, from an economic perspective, the investment in distributed RES in the Northeastern American market is not profitable at this time. Implementing DG as an energy policy may be justified when the economic benefits of avoided burdens are considered. However, this constitutes a significant challenge in policy implementation.

4. Conclusion

Despite their high initial cost, small-scale photovoltaic and wind electricity production technologies receive significant funding. In fact, incentive programs and tax rebates are commonly proposed to offset the economic burden of the initial capital that is required. However, such financial support would be fully justified and, consequently, more easily promoted, if the economic value of small-scale RES integration was clearly established. The objective of this paper is to assess the economic value of RES, including their environmental benefits, using hourly generation information in conjunction with hourly wholesale price data. The results of this study provide a better estimate of the bias that result from neglecting 1) the time pattern of hourly wholesale prices, 2) the impacts of carbon taxes on hourly wholesale prices and 3) the value of marginal hourly GHG emissions.

Selected RES include two types of grid-connected photovoltaic panels (3 kWp mono- and poly-crystalline) and three types of micro-wind turbines (1, 10 and 30 kW) modeled for different climatic conditions in Quebec (Canada). The cost of electricity is based on the technical performance of the studied RES using a life cycle costing methodology. The economic value of RES electricity is estimated with the 2006–2008 hourly wholesale electricity prices in Northeastern American markets.

Results show that distributed generation (DG) has no economic benefits using the selected RES, even with a US$100/tonne of CO_2-equivalent carbon tax. This finding remains the same when the value of the avoided GHG emissions is fully internalized, except for one scenario (micro-wind 30 kW). Our results are key to understanding the extent to which subsidies for distributed RES can be economically sustainable when these systems are integrated into regional networks driven by centralized electricity production.

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